

DEVICE FOR MEASURING THE RELATIVE ANGULAR POSITION OF TWO
BODIES WITH RESPECT TO A POINT, AND ARTICULAR PROSTHESIS
PROVIDED THEREWITH

BACKGROUND OF THE INVENTION

5 Field of the Invention

The present invention relates to a device for measuring the relative angular position of two bodies with respect to a point, and to an articular prosthesis provided therewith.

Description of the Related Art

- 10 As is known, active articular prostheses have been developed, which, when applied to a patient, enable a much more effective recovery of the functionality of the injured or missing limb than do traditional passive prostheses. In particular, active articular prostheses for the lower limbs (knee and ankle) tend to facilitate movement of the patient during deambulation.
- 15 Active articular prostheses comprise a pair of artificial skeletal members (for example, prostheses of tibia and femur), hinged to one another, so as to form an joint, and are provided with a control unit, an angular-position sensor, and an actuator, which is able to supply a torque between the artificial skeletal members of the joint. The angular-position sensor detects the relative angular
- 20 position of the skeletal members, and the control unit, on the basis of the information supplied by the angular-position sensor, operates the actuator so as to control the movement of flexo-extension of the joint, especially during deambulation.
- 25 In known articular prostheses, angular-position sensors of a resistive type (angular potentiometers) or of an inductive type are normally used. Angular potentiometers are used for obtaining voltage dividers with variable voltage-

division ratio. More precisely, an angular potentiometer is provided with a resistive element and a moving slider, in sliding electrical contact with the resistive element. The resistive element, fixed to one of the skeletal members, is thus divided into two resistive portions, and the division ratio between the two resistive portions
5 depends upon the position of the slider, which is fixed to the other skeletal member. The information on the angular position of the skeletal members is hence supplied by the value of the voltage-division ratio. Angular sensors of an inductive type are based upon detection of the current flowing in a first winding on account of the variations in a magnetic field generated by a second winding, which
10 is angularly movable with respect to the first winding. In particular, variations in the relative angular position of the two windings (each fixed to a respective skeletal member) modify the magnetic flux concatenated by the first winding, which is thus subject to an induced electromotive force and is traversed by a current.

Both of the types of sensors described, however, suffer from serious
15 drawbacks that limit the performance and possibility of use thereof. In particular, angular potentiometers are readily subject to failure, have considerable encumbrance and usually require an extremely accurate assembly, in so far as even minimal misalignments are critical for their operation. In addition, angular potentiometers show problems of mechanical wear, on account of the sliding
20 contacts. In the case of use for prostheses of the knee or ankle, these problems of wear are aggravated by the intensive use of the sensor. Angular sensors of an inductive type are more robust, have higher linearity, and do not present problems of mechanical wear. However, the encumbrance of inductive sensors is considerable, on account both of the electronic control circuits and of the shaft
25 necessary for connection of one of the windings to the respective skeletal member. Inductive sensors are hence far from suitable for being miniaturized and integrated in a prosthesis.

BRIEF SUMMARY OF THE INVENTION

An embodiment of the present invention is to provide a device for measuring the relative position of two bodies with respect to a point, and an articular prosthesis incorporating said device, which will be free from the
5 drawbacks described.

One embodiment of the invention is directed to a device for measuring the relative angular position of first and second bodies with respect to a point. The device includes a first measuring element and a second measuring element, relatively movable with respect to one another and connectable to the
10 first body and, respectively, the second body. The first measuring element comprises a first inclination sensor, having a first detection axis and supplying a first inclination signal, correlated to a first angle of inclination of said first detection axis with respect to a reference axis. The second measuring element comprises a
15 second inclination sensor, having a second detection axis and supplying a second inclination signal, correlated to a second angle of inclination of said second detection axis with respect to said reference axis.

BRIEF DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWINGS

For a better understanding of the invention, there is now described an embodiment thereof, purely by way of non-limiting example and with reference
20 to the annexed drawings, in which:

Figure 1 is a schematic plan view of a known inertial sensor;

Figures 2a and 2b are schematic illustrations of the inertial sensor of Figure 1 in different operative configurations;

Figure 3 is a block diagram of a prosthesis incorporating the device
25 according to the present invention;

Figure 4 is a schematic illustration of the prosthesis of Figure 3 in a different operative configuration; and

Figure 5 is a more detailed block diagram of a part of the diagram of Figure 3.

DETAILED DESCRIPTION OF THE INVENTION

Illustrated in Figure 1 is a linear inertial sensor 1 of micro-electro-mechanical (or MEMS) type, in itself known, which has a preferential detection axis A; in particular, in the configuration of Figure 1, the detection axis A of the sensor 1 is horizontal and hence perpendicular to the direction of the acceleration of gravity G. The inertial sensor 1 comprises a stator 2 and a moving element 3, connected to one another by means of springs 4 in such a way that the moving element 3 can translate parallel to the detection axis A.

The stator 2 and the moving element 3 are provided with a plurality of first and second stator electrodes 5', 5'', and, respectively, with a plurality of moving electrodes 6. Each moving electrode 6 is comprised between two respective stator electrodes 5', 5'', which it is partially facing; consequently, each moving electrode 6 forms with the two mutually adjacent fixed electrodes 5', 5'' a first capacitor and, respectively, a second capacitor having plane and parallel faces. In addition, all the first stator electrodes 5' are connected to a first stator terminal 1a, and all the second stator electrodes 5'' are connected to a second stator terminal 1b, whereas the moving electrodes 6 are connected to ground.

From the electrical standpoint, then, the inertial sensor 1 may be represented ideally by a first equivalent capacitor 8 and a second equivalent capacitor 9 (here illustrated with a dashed line); the equivalent capacitor 8 has its first terminal connected to the first stator terminal 1a, and the equivalent capacitor 9 has its first terminal connected to the second stator terminal 1b, and they each have their second terminal connected to ground. In addition, the first and second equivalent capacitors 8, 9 have variable capacitances correlated to the position of the moving element 3 with respect to the rotor 2; in particular, the capacitances of the equivalent capacitors 8, 9 at rest are equal and are unbalanced in the presence of

an acceleration oriented according to the detection axis A. The capacitive unbalancing is hence indicative of the component of the resultant of the forces acting on the moving element 3 parallel to the detection axis A.

In the configuration of Figure 1, if the acceleration of gravity G is perpendicular to the detection axis A, then the force of gravity F acting on the moving element 3 does not bring about any displacement of the moving element 3 itself. Figures 2a and 2b, instead, illustrate, respectively, a first configuration in which the detection axis A is vertical and hence parallel to the force of gravity F, and a second configuration in which the detection axis A is inclined at an angle φ with respect to a horizontal axis (and hence forms an angle of $90^\circ - \varphi$ with the direction of the acceleration of gravity G). In the case of Figure 2b, the component F_A of the force of gravity F along the detection axis A is:

$$F_A = F \sin \varphi \quad (1)$$

Clearly, the capacitive unbalancing of the inertial sensor 1 is proportional to the component F_A . From equation (1), the inclination of the detection axis A with respect to the horizontal reference axis R can be readily derived:

$$\varphi = \arcsin (F_A/F) \quad (2)$$

In practice, then, the inertial sensor 1 can be used as an inclinometer. With reference to Figure 3, an articular prosthesis 10 built according to one embodiment of the present invention, in particular a knee prosthesis, comprises an artificial femur 11 and tibia 12, a device 13 for measuring the relative angular position of the femur 11 and tibia 12, a control unit 14, and an actuator 15. In Figure 3, the femur 11 and the tibia 12 are represented schematically by rods, having respective ends connected to one another by a hinge 16.

The device 13 comprises a first inertial sensor 17 and a second inertial sensor 18, and a processing unit 19, connected to the control unit 14. The first inertial sensor 17 and the second inertial sensor 18 are identical to the inertial

sensor 1 of Figure 1, have respective preferential detection axes A_1 , A_2 , and are mounted on the femur 11 and, respectively, on the tibia 12. More precisely, the first and second inertial sensors 11, 12 are basically perpendicular to the axes of the femur 11 and of the tibia 12, in such a way that, when the femur 11 and the tibia 12 are aligned in the vertical direction, the detection axes A_1 , A_2 of the first and second inertial sensors 17, 18 are horizontal and hence perpendicular to the direction of the acceleration of gravity G (configuration of Figure 3). In addition, the detection axes A_1 , A_2 of the first and second inertial sensors 17, 18, respectively, are basically coplanar.

Outputs 17A, 18A of the first and second inertial sensors 17, 18, respectively, are moreover connected to the processing unit 19, to supply a first inclination signal S_1 and a second inclination signal S_2 , respectively. In particular, the first and second inclination signals S_1 , S_2 are correlated to the capacitive unbalancing caused by the resultants of the forces acting parallel to the first detection axis A_1 of the first inertial sensor 11 and to the second detection axis A_2 of the second inertial sensor 12, respectively. On the basis of the first and second inclination signals S_1 , S_2 , the processing unit 19 supplies the control unit 14 with the value of an angle θ comprised between the axes of the femur 11 and of the tibia 12 (see also Figure 4). In turn, the control unit 14 has an output that is connected to the actuator 15 and supplies a control signal S_C correlated to the value of the angle θ . In addition, the control unit 14 and the processing unit 19 are preferably integrated in a single semiconductor body.

The actuator 15 is connected to the femur 11 and to the tibia 12 and, on the basis of the control signal S_C , supplies a torque C which tends to bring about a relative rotation of the femur 11 and the tibia 12 about the hinge 16.

Figure 4 illustrates a different configuration of the articular prosthesis 10 in use. In this case, the femur 11 and the tibia 12 form with respect to one another an angle θ smaller than 180° , whereas the first and second axes of detection A_1 , A_2 form a first angle α_1 and, respectively, a second angle α_2 with respect to a horizontal

reference axis R. More precisely, the angle θ is defined by the straight lines joining the hinge 16 and the first and second inertial sensors 17, 18. These straight lines coincide substantially with the longitudinal axes of the femur 11 and the tibia 12.

Between the angles α_1 , α_2 , and θ there exists the following relation:

5
$$\theta = 180^\circ - \alpha_1 - \alpha_2 \quad (3)$$

In particular, the angles α_1 , α_2 are considered positive if they correspond to clockwise rotations and negative otherwise. In addition, the inclination signals S_1 , S_2 are given by the following relations:

$$S_1 = S_{1MAX} \sin \alpha_1 \quad (4)$$

10
$$S_2 = S_{2MAX} \sin \alpha_2 \quad (5)$$

where S_{1MAX} and S_{2MAX} are the maximum values of the inclination signals S_1 and S_2 , respectively, that can be measured when $\alpha_1 = 90^\circ$ and when $\alpha_2 = 90^\circ$, respectively.

The control signal S_c supplied by the control unit 19 is correlated to
15 the angle θ between the femur 11 and the tibia 12, as explained hereinafter, and, in practice, enables operation of the actuator 15 according to the movement of the patient. In particular, the actuator 15 can be used as brake when the prosthesis is loaded in the stance phase during deambulation, so as to render the deambulation itself more natural.

20 As is illustrated in Figure 5, the processing unit 19 comprises a first processing line 20, which receives at input the first inclination signal S_1 , a second processing line 21, which receives at input the second inclination signal S_2 , and a calculation unit 22.

The first and second processing lines 20, 21 comprise respective
25 analog-to-digital converters 23A, 23B, spike-suppression units 24A, 24B, filtering units 25A, 25B and arcsine tables 26A, 26B, connected to one another in cascaded fashion. The spike-suppression units 24A, 24B are per se known and, preferably, are of the type described in the US Patent No. 6,677,812 in the

name of STMicroelectronics, the assignee of the present invention. The spike-suppression units 24A, 24B and the filtering units 25A, 25B, which are also known and are preferably of a numeric type, eliminate, from the signals S_1 , S_2 , the noise components due, for example, to vibrations transmitted to the inertial sensors 17, 18 in the phase of stance or of swing during deambulation. In practice, the filtering units 25A, 25B of the first and second processing lines 20, 21 supply the respective arcsine tables 26A, 26B with a first filtered inclination signal S_{1F} and a second filtered inclination signal S_{2F} , respectively, which are correlated just to the contribution of the force of gravity F and from which it is possible to derive the values of the first and second angles α_1 , α_2 .

The arcsine tables 26A, 26B (look-up tables) of the first and second processing lines 20, 21 have outputs connected to the calculation unit 22 and supply values of the first angle α_1 , and second angles α_2 , respectively, which are selected in a known way on the basis of the values of the first and second filtered inclination signals S_{1F} , S_{2F} , respectively. The calculation unit 22 determines the value of the angle θ according to the expression (3) and supplies it to the control unit 14 (Figure 3), which, as mentioned previously, determines the value of the control signal S_C to be supplied to the actuator 15.

The advantages of the invention emerge clearly from what has been described above and are mainly due to the use of MEMS inertial sensors. These inertial sensors, in fact, are extremely compact and hence particularly suited to miniaturization. Furthermore, they do not present problems of installation on artificial skeletal members, and possible misalignments can readily be compensated by providing an offset angle during calibration. Another advantage of MEMS sensors is that the mobile parts are basically friction-free, and hence mechanical wear is minimal. In addition, power absorption of MEMS sensors is practically negligible.

In addition, the device described enables the posture of the patient to be determined, and the actuator to be deactivated or set in a stand-by condition

when the patient is not deambulating. In particular, the device is able to recognize when the patient is in a sitting condition ($\alpha_1 \cong 90^\circ$, $\alpha_2 \cong 0$) and when the patient is lying down ($\alpha_1 \cong \alpha_2 \cong -90^\circ$). In this way, it is possible to reduce power consumption significantly.

5 All of the above U.S. patents, U.S. patent application publications, U.S. patent applications, foreign patents, foreign patent applications and non-patent publications referred to in this specification and/or listed in the Application Data Sheet are incorporated herein by reference, in their entirety.

Finally, it is evident that modifications and variations may be made to
10 the device described herein, without departing from the scope of the present invention. First, the device may be integrated in a prosthesis of a different joint, in particular of the ankle. Furthermore, the sensors could be differently oriented with respect to the skeletal members (for example, they could be parallel to the axes of the skeletal members) and use reference directions other than the horizontal
15 direction for calculation of the angles of inclination α_1 , α_2 . Of course, it is possible to base the calculation of the angle θ on different angles. The arcsine tables could then be replaced with different circuits capable of carrying out the operation of extraction of the arcsine either via software or directly via hardware.